The Effects of Viterbi Decoder Node Synchronization Losses on the Telemetry Receiving System

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The Viterbi decoders currently used by the Deep Space Network (DSN) use an algorithm for maintaining node synchronization that breaks down at bit signal-to-noise ratios (SNRs) of about 2.0 dB. In this report, it is shown that this can become an important consideration when the effects of noisy carrier referencing are combined with the lower SNRs that are expected at Voyager 2 Uranus and Neptune encounters. Depending on the available carrier power, node synchronization losses of between 0.85 and 1.25 dB can be expected in addition to the radio loss.

I. Introduction

Most present and all planned deep space missions make use of convolutional coding. The NASA standard (7, 1/2) convolutional code is used in conjunction with Viterbi, or "maximum likelihood", decoding. Figure 1 shows an encoder for this convolutional code. The input information bits $i_1 i_2 i_3 \ldots$ are shifted into a register. This register is used to generate two parity checks each time a new information bit is entered. A commutator interleaves these parity checks to produce the coded output stream $a_1 b_1 a_2 b_2 a_3 b_3 \ldots$.

One advantage to convolutional coding is that decoding may begin at any symbol a_j in the output stream. This is in contrast to block coding in which the decoder must be aligned with codeword boundaries. A convolutional decoding system must, however, be capable of distinguishing between the a_js and the b_js in order to function properly. The process of determining which of the symbols are the a_js is called "node synchronization".

The Viterbi decoders that are currently used by the DSN have internal hardware for determining node synchronization. The algorithm that is used was optimized for the larger bit SNRs that were being considered at the time they were built. Tests conducted in 1979 in the Telecommunications Development Laboratory (TDL) have shown that this node synchronization algorithm breaks down at a bit SNR of about 2.5 dB when the carrier tracking loop SNR is 16 dB (Ref. 1). At bit SNRs below this value, the Viterbi decoder always decides that it is out of synchronization – regardless of whether it really is. This means that it oscillates between proper and improper node synchronization.

With the advent of concatenated Reed-Solomon/convolutional coding, poor node synchronization will become a more critical factor in overall channel performance. This is due to the fact that the Viterbi decoders will be operated at bit error rates of about 10^{-2} to achieve a concatenated bit error rate of 10^{-5} (Ref. 2). This corresponds to an E_b/N_0 of about 2 dB at the input of the Viterbi decoder, which means that the telemetry receiving system will be operating in the region of poor node synchronization.

The theory developed in this article predicts that between 0.85 and 1.25 dB will be lost due to the poor performance of the current DSN Viterbi decoders' node synchronization algorithm (for the convolutional-only channel) at SNRs that are typical of the Voyager 2 Uranus encounter. One solution to this problem is to disable the internal node synchronization hardware in the existing Viterbi decoders. A new external node synchronization logic could then be implemented. One such algorithm is described in Ref. 3. Another algorithm which makes use of frame headers in the data stream was analyzed by Laif Swanson, Section 331 (personal correspondence).

II. The Model

A simplified block diagram of a DSN telemetry system is shown in Fig. 2. Information bits produced by the spacecraft instruments are first convolutionally encoded. The encoded bits, which will be referred to as "channel symbols" are amplitude-modulated on a square wave subcarrier. The resulting signal phase-modulates a high-frequency sinusoidal carrier which is amplified and transmitted over the space channel. The channel is assumed to add an independent white Gaussian noise to this signal. On the ground, the carrier is demodulated in the receiver, and the subcarrier is stripped off by the Subcarrier Demodulation Assembly (SDA). The Symbol Synchronizer Assembly (SSA) recovers a noisy version of the channel symbol stream, which is sent to the Viterbi decoder for decoding. The decoder performs its own node synchronization.

For modeling purposes, only losses occurring in the space channel, receiver, and decoder were considered for this report. These are certainly the most important losses since the loop SNRs of the SDA and SSA are typically much higher than that of the receiver.

Suppose that the bit SNR of the signal incident on the ground antenna is E_b/N_0. The result of a phase estimate error ϕ in the receiver tracking loop would be an output SNR of $(E_b/N_0)\cos^2\phi$ (Ref. 5). Suppose also that the bit error rate at the output of the Viterbi decoder is $f(x)$ when the input bit SNR to the decoder is x. Then a constant phase error of ϕ in the receiver will produce an average decoded bit error rate of $f[(E_b/N_0)\cos^2\phi]$.

Assume now that the phase error ϕ is changing slowly compared to the decision length of the Viterbi decoder. Then the overall average decoded bit error rate of the system is given by

$$P_b = \int_{-\pi}^{\pi} f\,[(E_b/N_0)\cos^2\phi]\; p(\phi)\, d\phi \tag{1}$$

where $p(\phi)$ is the density of the phase error ϕ. This is known as the high rate model.

To illustrate the applicability of the high rate model assumption, consider a typical Voyager 2 Uranus encounter scenario. A typical data rate would be R_b = 19.2 kbps. The bandwidth of a Block IV receiver for the encounter would be 30 Hz. This means that a phase error ϕ would remain relatively constant over a period of about 600 bits – much longer than the path memory in the present Viterbi decoders.

The density $p(\phi)$ is derived in Ref. 6 to be

$$p(\phi) = \frac{\exp(\rho\cos\phi)}{2\pi I_0(\rho)}$$

where ρ is the loop SNR of the receiver tracking loop, and I_0 is the zero order modified Bessel function.

The Viterbi decoder error function $f(x)$ will be taken to be the ideal performance curve exhibited in Ref. 4 with the exception that $f(x) = 1/2$ whenever x is below some value T, the Viterbi decoder node synchronization threshold. In this region, it is assumed that the decoder is continuously resynchronizing and hence produces random output.

III. Numerical Results

Numerical methods were used to calculate the Viterbi bit error rate as a function of E_b/N_0, carrier tracking loop SNR, and node synchronization threshold using Eq. (1). It was observed that the performance predicted by the model for a node synchronization threshold of 2.0 dB and a carrier tracking loop SNR of 16 dB closely approximates the actual performance data generated in the TDL (Ref. 1). This evidence supports the hypothesis that the present Viterbi decoders do not maintain proper node synchronization below 2.0 dB of E_b/N_0 in a perfect carrier tracking environment. Figure 3 shows the TDL data points as well as the performance predicted by the model. A bit error rate curve for a loop SNR of 16 dB but with perfect node synchronization is included for comparison.

Graphs of Viterbi decoder bit error rate performance for node synchronization thresholds of 0.0 and 2.0 dB appear in Figs. 4 and 5, respectively. The 0.0-dB curves agree very well with the data that are exhibited in Ref. 4 for a single aperture and perfect node synchronization. The curves of Figs. 4 and 5 were used to generate the two radio loss curves shown in Fig. 6. Radio loss is defined to be the ratio of the bit SNR needed to achieve some predetermined bit error rate in a degraded system to that required in an ideal system. In this case, the ideal system is taken to be the ideal Viterbi decoder performance as given in Ref. 4, and the fixed bit error rate is 0.005, the generally accepted upper bound for uncompressed image transmission. The difference between the two curves represents the incremental SNR loss due to poor node synchronization performance. Data from design control tables predict that for Voyager 2 Uranus encounter (at a data rate of 19.2 kbps, a modulation index of 76° and 90% weather), a 64-meter antenna would have an associated carrier tracking loop SNR of about 13 dB, while a 34-meter antenna would have one of about 11 dB. The associated node synchronization losses for these unarrayed antennas would therefore be 0.85 and 1.25 dB, respectively.

Plots of the loss due to poor node synchronization as a function of node synchronization threshold appear in Fig. 7 for various carrier tracking loop SNRs. These represent the additional degradations over the carrier phase jitter losses. It is easily seen from these graphs how much can be gained by improving the node synchronization algorithm of the Viterbi decoders.

IV. Conclusions

The model developed in this article predicts that as much as 0.85 dB may be gained at Voyager 2 Uranus encounter in a 64-meter-aperture receiving system by lowering the current Viterbi decoder node synchronization threshold from 2.0 to 0.0 dB. This can be accomplished in three ways. One is to replace the current Viterbi decoders with new decoders that could be designed to work well in the low SNR environment that will exist in Voyager's far planetary encounters. The other two ways involve modifying the current decoders so that they no longer determine their node synchronization internally. If this modification is done, then either the scheme described in Ref. 3 or a scheme that uses frame header information in the symbol stream may be implemented.

In the immediate future, this model will be extended to the concatenated Reed-Solomon/convolutional channel where the effects of poor node synchronization are expected to be even more pronounced than in the convolutional-only channel.

References

1. Liu, K. Y., and Lee, J. J., "An Experimental Study of the Concatenated Reed-Solomon/Viterbi Channel Coding System and Its Impact on Space Communications," Publication 81-58, Jet Propulsion Laboratory, Pasadena, Calif., Aug. 15, 1981.

2. Miller, R. L., Deutsch, L. J., and Butman, S. A., "On the Error Statistics of Viterbi Decoding and the Performance of Concatenated Codes," Publication 81-9, Jet Propulsion Laboratory, Pasadena, Calif., Sep. 1, 1981.

3. Greenhall, C. A., Miller, R. L., and Butman, S. A., "A Quick-Look Decoder with Isolated Error Correction and Node Synchronization," *IEEE Trans. Comm.*, Vol. COM-29, No. 7, July 1981.

4. Divsalar, D., and Yuen, J. H., "Improved Carrier Tracking Performance with Coupled Phase-Locked Loops," in *TDA Progress Report 42-66*, Jet Propulsion Laboratory, Pasadena, Calif., Dec. 15, 1981.

5. Deutsch, L. J., Miller, R. L., and Butman, S. A., "New Results on Antenna Arraying: Part 1," *TDA Progress Report 42-62, January and February 1981,* Jet Propulsion Laboratory, Pasadena, Calif.

6. Lindsey, W. C., and Simon, M. K., *Telecommunications Systems Engineering*, Prentice Hall, Inc., N. J., 1973.

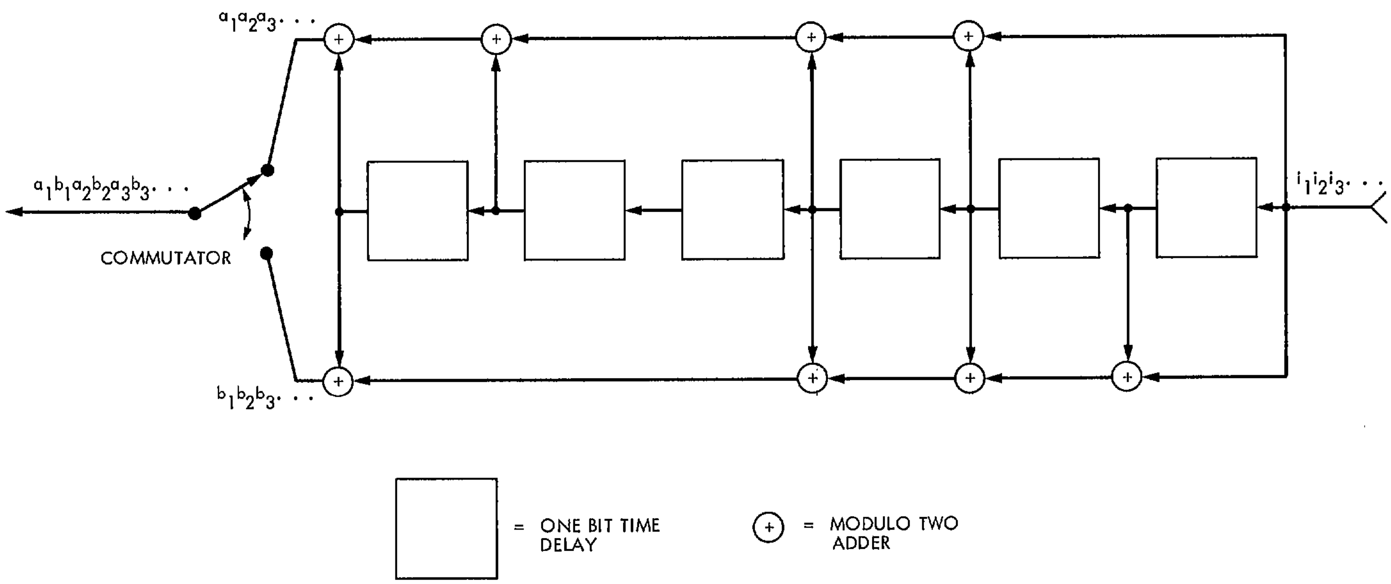

Fig. 1. Conceptual diagram of a (7 1/2) convolutional encoder

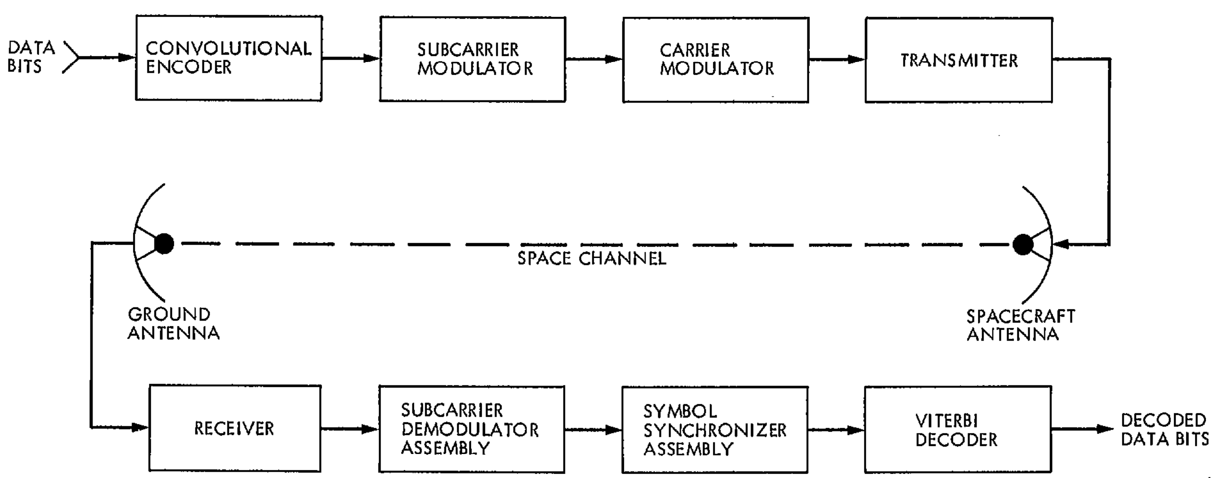

Fig. 2. Simplified block diagram of the DSN telemetry system

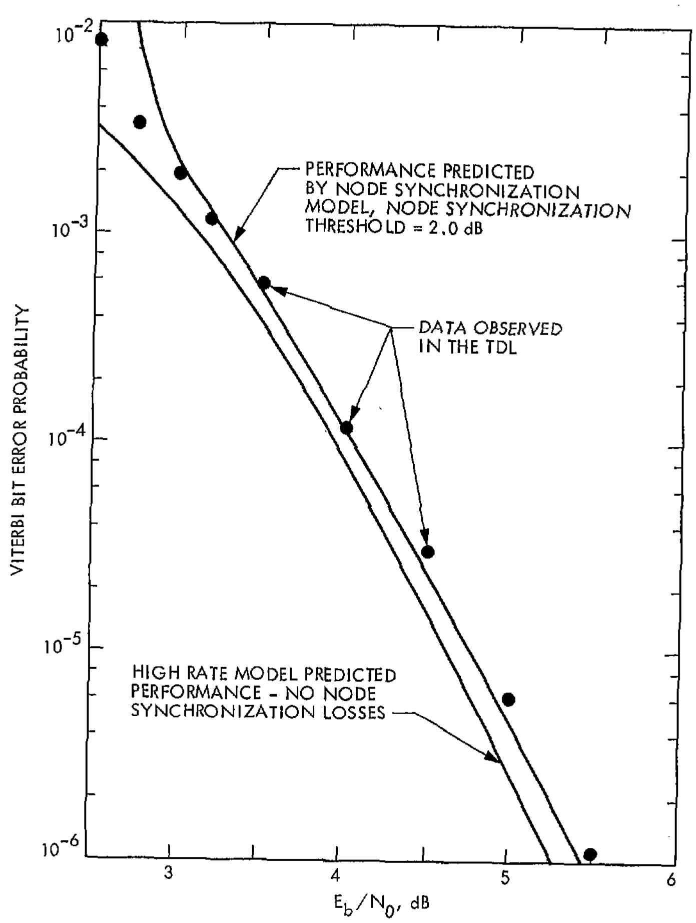

Fig. 3. Viterbi-decoder bit error rate performance with a carrier tracking loop SNR of 16 dB

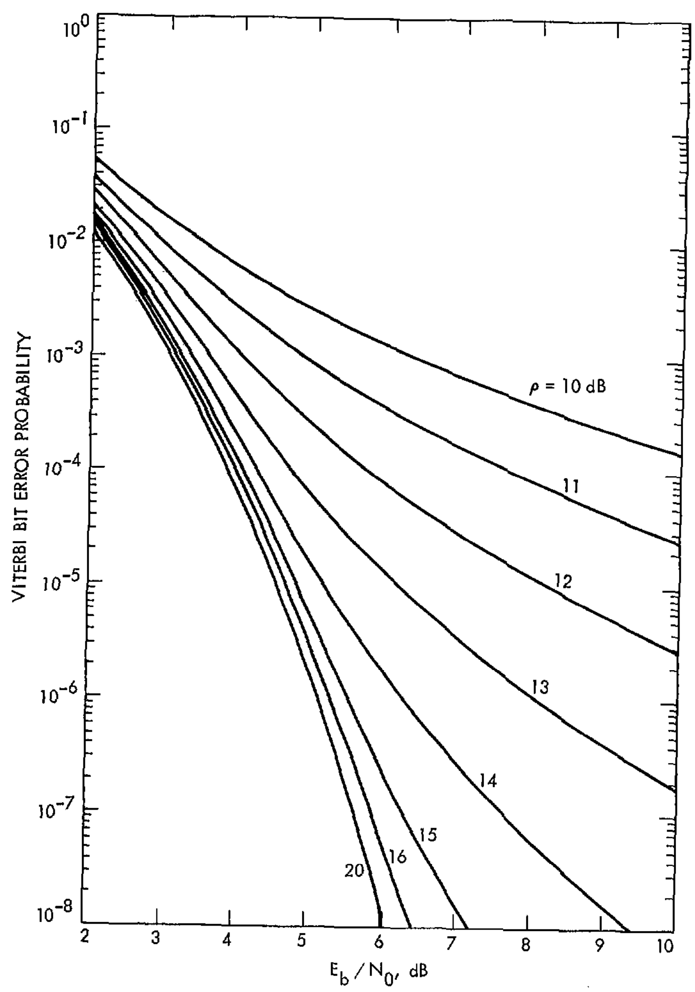

Fig. 4. Viterbi-decoded bit error rate for various carrier tracking loop SNRs, node synchronization threshold = 0.0 dB

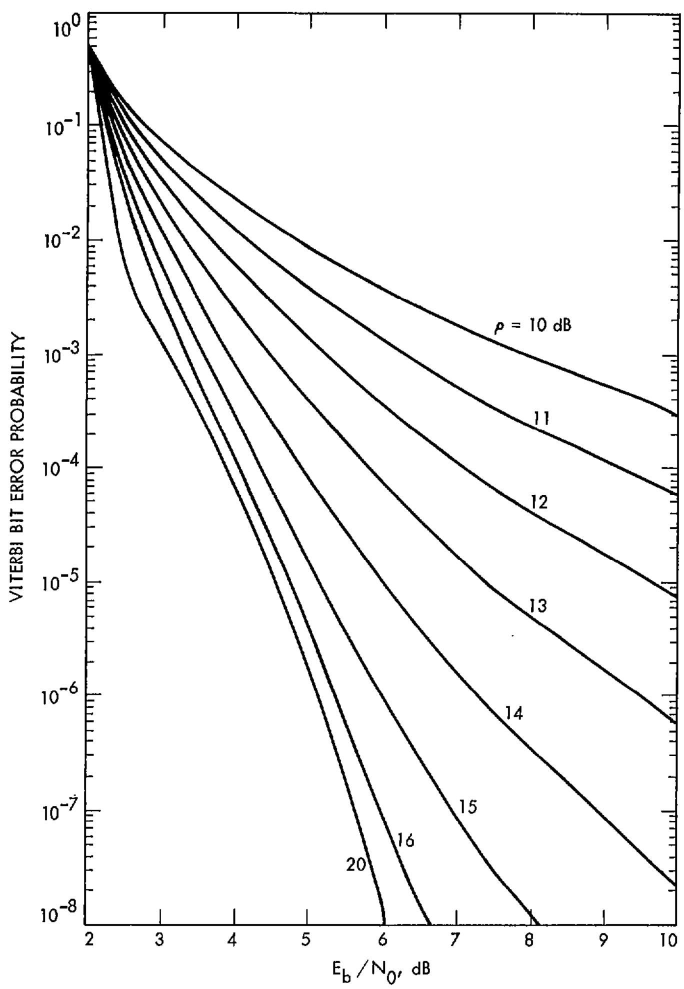

Fig. 5. Viterbi-decoded bit error rate for various carrier tracking loop SNRs, node synchronization threshold = 2.0 dB

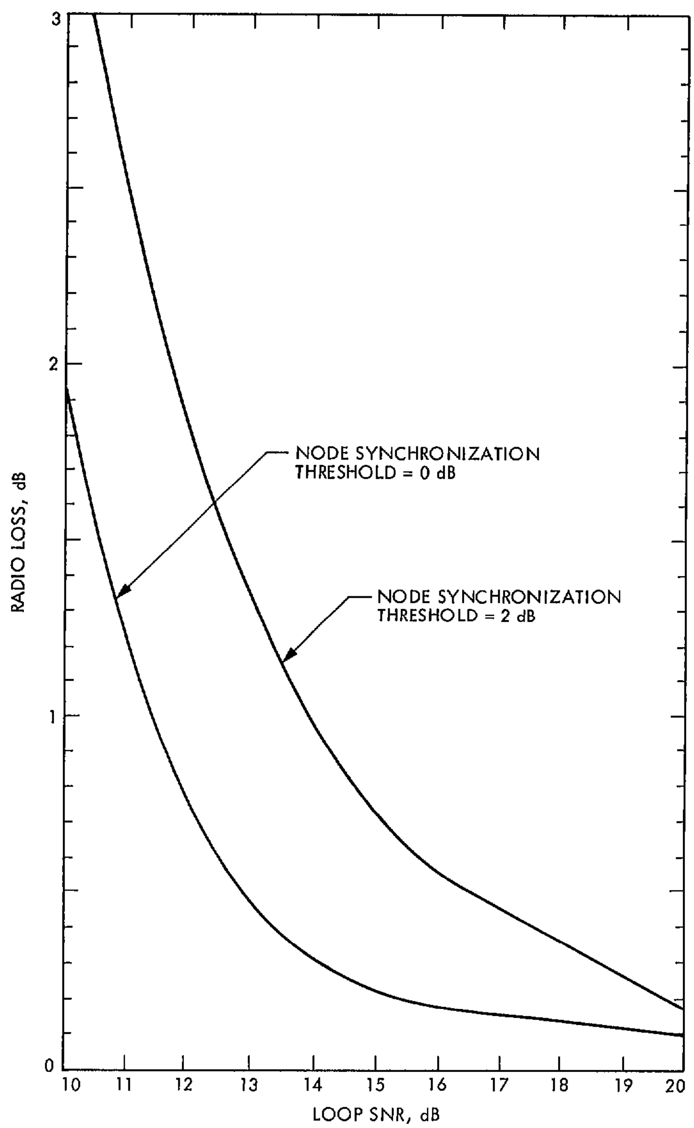

Fig. 6. Radio loss at BER = .005 at node synchronization thresholds of 0.0 dB and 2.0 dB

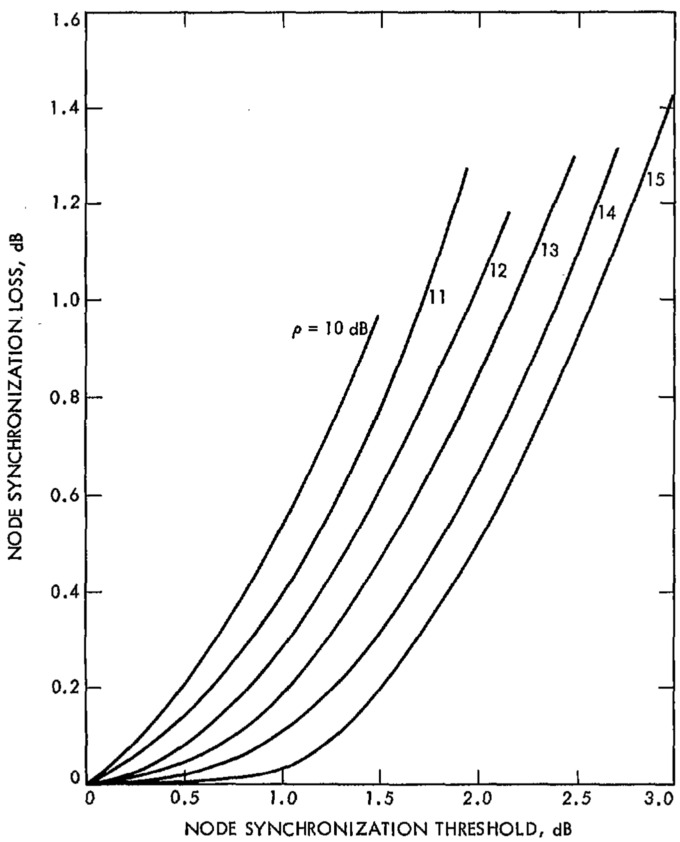

Fig. 7. Node synchronization loss for various carrier tracking loop SNRs